High temperature behaviour of polypropylene fibres reinforced mortars

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Abstract

The aim of this paper is primarily experimental and is intended to analyse the behaviour of two cementitious materials, before and after heat treatment: one unreinforced (i.e. without fibres) and the other reinforced (with polypropylene fibres).

At room temperature and after heating up to 500°C, the bending strength is improved by the presences of fibres. The residual young modulus is slightly higher for the fibres reinforced samples.

As the temperature increases, the strength gain due to fibres inclusion is reduced. Beyond 500°C, the bending strength is lower for the fibre reinforced cementitious material compared to those without fibres.

Fracture energy is also improved for the fibre mortars at room temperature. At 400°C this improvement decreases gradually with the introduction of polypropylene fibres. Beyond this temperature and due to the introduction of polypropylene fibres, the fracture energy is reduced.

Another test is developed: rapid heating due to exposure to a flame. The temperature in the front side reaches in few seconds 1000°C. At this temperature and after one hour of exposure, the opposite side reached 140°C. After cooling, the punching shear strength of the fibre mortar is definitely weaker than of the mortar without fibre.

KEYWORDS

Polypropylene fibre mortar, Mechanical behaviour, Fracture energy, Fire test, Spalling, Punching shear test

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1. INTRODUCTION

The polypropylene fibres are used in the mortars and concrete to decrease the plastic shrinkage, cracking and micro-cracking of surface [1]. They increase cohesion and reduce slump [2]. While inclusion of metal fibres improves the fire resistance [3], the presence of polypropylene fibres in the material does not [4]. Only the effect limiting spalling at high temperatures is about to be unanimously recognized. This action is primarily studied in high performance concrete i.e. with low water/cement ratio [4-6].

However, during a fire, very strong thermal gradients take place in first centimetres of concrete and the thermal damage rapidly decreases from a maximum to nil [7, 8]. So, in these first centimetres, where temperatures are less than a critical temperature, polypropylene fibres should still have an effect on mechanical behaviour. The objective of this work is then to examine the effect of the temperature on the residual behaviour of the polypropylene fibre mortars. In addition to the classical flexural strength, we focus to the cracking behaviour and more particularly to the fracture energy and to the stress intensity factor. These characteristics are important in connection with the crack resistance and in particular with the resistance to spalling.

In this paper two type of heating were studied: low rate heating (2°C/min) and high rate heating (rate similar to ISO 834 standard fire). These two studies allow to separate physicochemical effects and temperature gradient effect.

2. MATERIALS

To ensure an effective bridging of the cracks (to limit the crack opening), the dimension of the selected fibres must be greater than those of the aggregates [4]. At room temperature, the aim of the polypropylene fibres in the composite matrix is to ensure a macro cracking bridging and to maintain high post peak strength at a very large crack [9]. In this study cementitious mortars were studied, and then, 12 mm monofilament polypropylene fibres were chosen. Characteristics of the fibres (given supplier: SIKA) are detailed in table 1.

Table 1: Characteristics of test fibres (given SIKA)

Fibre	Length L (mm)	Diameter Ø (µm)	Ratio L/Ø	Density ρ (kg/m^3)	Young Modulus E (GPa)	Melting point (°C)	Tensile strength σ (GPa)
Polypropylene	12	18	667	910	6	170	0,55

A Portland cement is used: CEM1 52,5 N CE CP2 NF. This cement is made up mainly of clinker 95%, whose details of the chemical and mineralogical compositions are reported in table 2.

The mortars are made with standardized sand according to CEN 196-1 standard with the ISO 679. The mass proportions of cement, sand and water are 1:3:0.5. The volume proportion of added fibres in the fibre mortars is 0.58% (i.e. 5.2 kg/m^3). Water was added to cement and mixed to obtain a homogeneous paste; sand then gradually added to the paste and mixed until homogeneous. Fibres were added at the final stage and dispersed manually. The constituents were mixed for two minutes after the introduction of the fibres.

The specimens were then stored in a wet room (20°C, 95% RH) for 7 days and then stored in dry room (20°C, 50% RH) up to an age of 28 days. Under these conditions, a significant portion of free water in the cement matrix had evaporated [10].

Table 2: Chemical and mineralogical composition of cement CEM I 52,5.

Elements	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	NaO_2	SO_3	IR	LOI	Free CaO
%	22.40	2.96	2.33	66.60	0.95	0.15	0.10	2.13	0.20	1.59	0.50
			C_3S = 65.3		C_2S = 18.6		C_3A = 4.35		C_4AF = 7.14		

IR : insoluble residue; LOI : loss on ignition.

3. SLOW HEATING

3.1. Heat exposure in an oven

Samples, 4x4x16 cm^3, were heated in an electric furnace to the desired temperature at a rate of 2°C/min. The exposure temperature was maintained during one hour (1h) and cooling to room temperature was carried out in the closed and disconnected furnace (approximately -0.3°C/min). The controlled temperature is measured in oven chamber (i.e. not in samples). This process conducts to low thermal gradients. The damages in mortar are mainly of physicochemical origin [11].

3.2. Flexural strength

After cooling, samples were then tested in a four-point bending configuration. Six specimens were tested for each condition (mortar type and heating temperature). The load is measure with a 50 kN load cell. A template is attached to the specimen to measure deflection using two LVDTs (+/- 1mm) (figure 1).

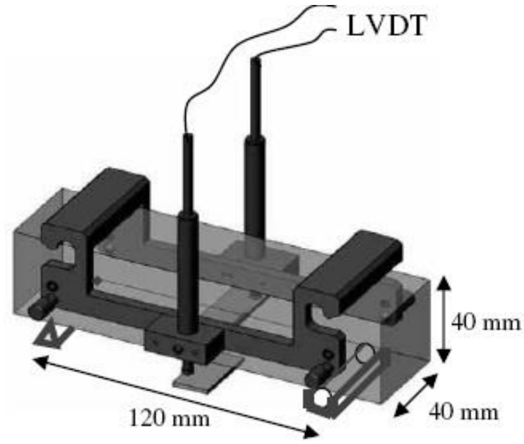

Figure 1: Four-point sample with measuring t.

The bending test results carried out on unreinforced mortar (MN) and fibre reinforced mortar (MNP) are presented in figure 2. The post peak residual load clearly highlights the role of fibres when samples are not heated. The stress transfer between the faces of the cracks is significant and result is an increased ductility. As already observed by other authors [12-14], this phenomenon attenuates very quickly between 400 and 500°C and disappear beyond 500°C. Figure 3 represents the evolution of the bending strength with respect to the exposure temperature. The polypropylene fibres have a positive role until 400°C as it was stated previously. The experimental values are reported in table 3.

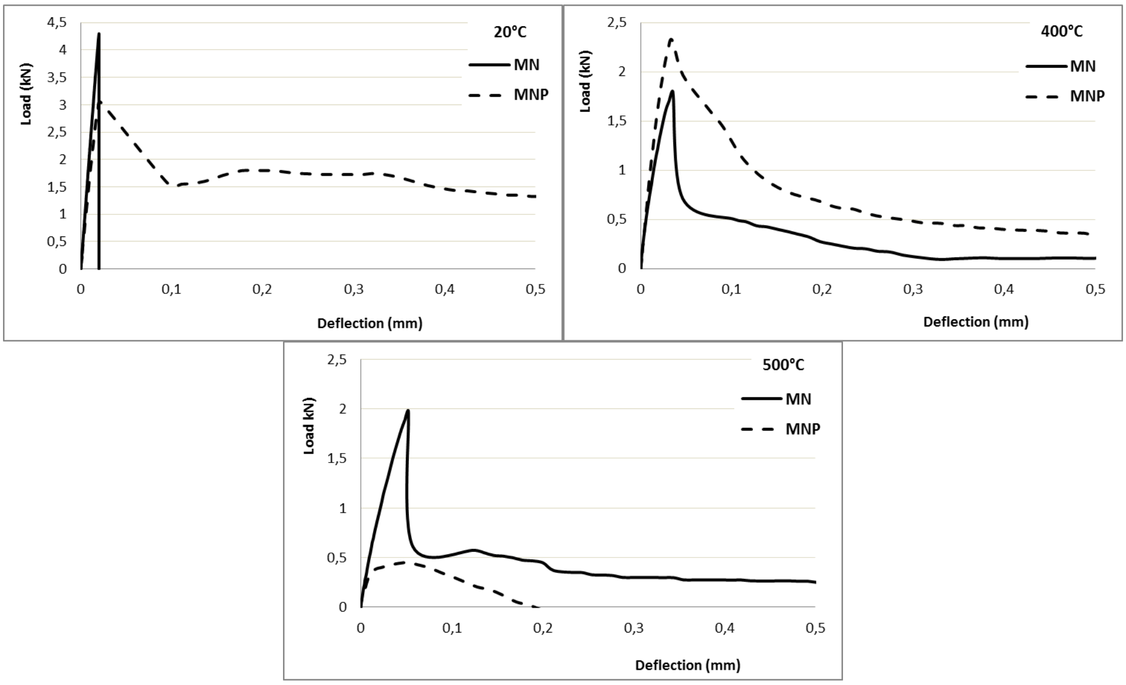

Figure 2: Representative curves of behaviour of the unreinforced mortar not (MN) and reinforced the 0.58% volume one of polypropylene fibres (MNP) in four-point bending test.

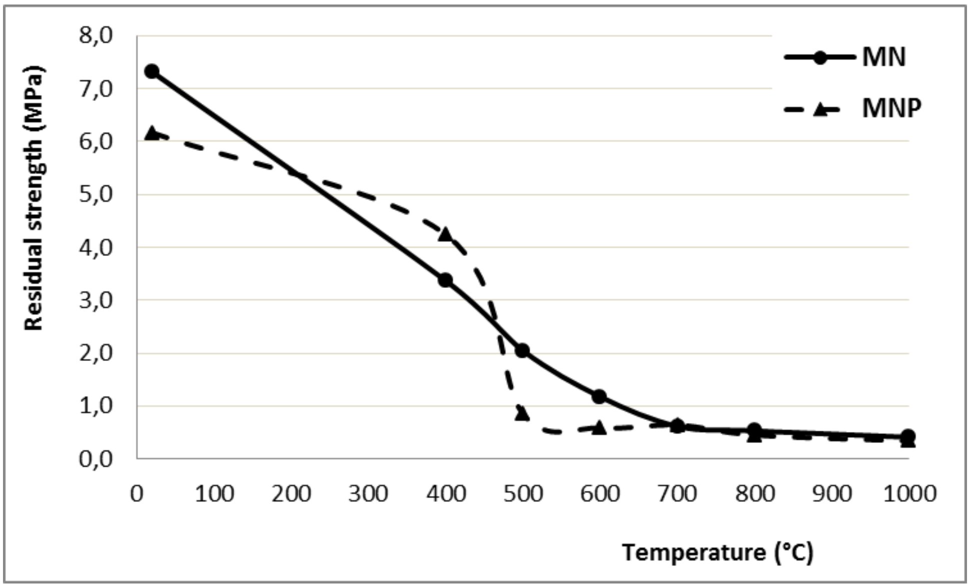

Figure 3: Evolution of the four-point bending tensile strengths of the mortars with respect to the exposure temperature (rate: 2°C/min).

Table 3: Evolution of the bending tensile stress (MPa) with temperature**.**

Mortar	T°C	20°C	400°C	500°C
MN		7.3	3.4	2.0
MNP		6.2	4.2	0.8

3.3. Young modulus

Young modulus is defined as the elastic (and linear) stage of the load-deflection curve. The evolution of the residual Young modulus with respect to the exposure temperature is shown in figure 4 and table 4. According to the test results, we notice that the modulus of the sample with fibre is greater than that of the non-fibre samples. The variation is accentuated until 400°C. At 500°C; they are identical and beyond this temperature; the young modulus of the fibred samples becomes almost zero.

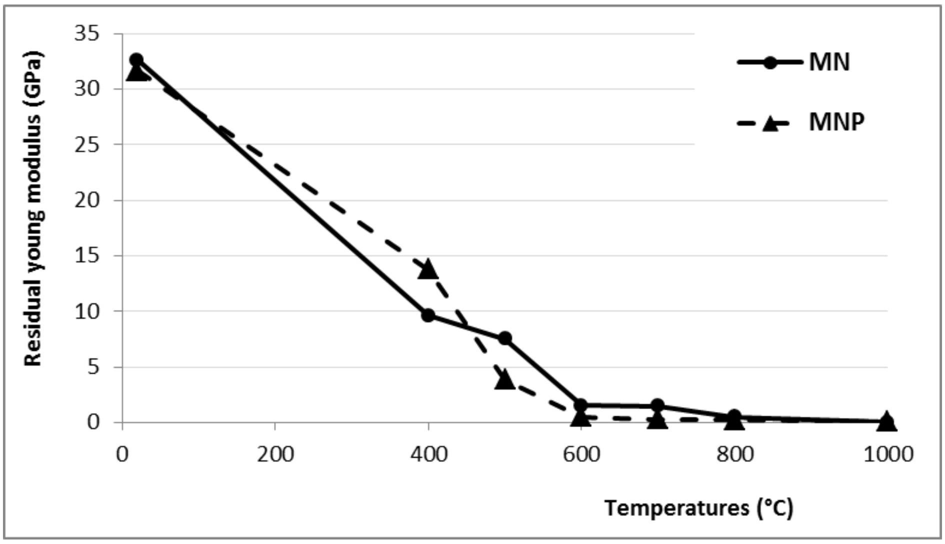

Figure 4: Residual Young modulus (four-point bending test) vs. temperature of the heat treatment

Table 4: Young modulus (GPa) vs. temperature.

Mortar	T°C	20°C	400°C	500°C
MN		32.6	9.6	7.5
MNP		31.6	13.8	3.8

3.4. Fracture energy

The fracture energy is defined as the area under the stress-strain curve of the four-point bending test [15]. Figure 5 and table 5 show the test results of the fracture energy with respect to the exposure temperature. When the samples are not heated, the fracture energy of the fibre specimen is about three times the energy of the non-fibre sample. This difference in fracture energy tends to converge and nullify at about 500°C. Above 500°C, gain increase in fracture energy decreases for samples with fibres.

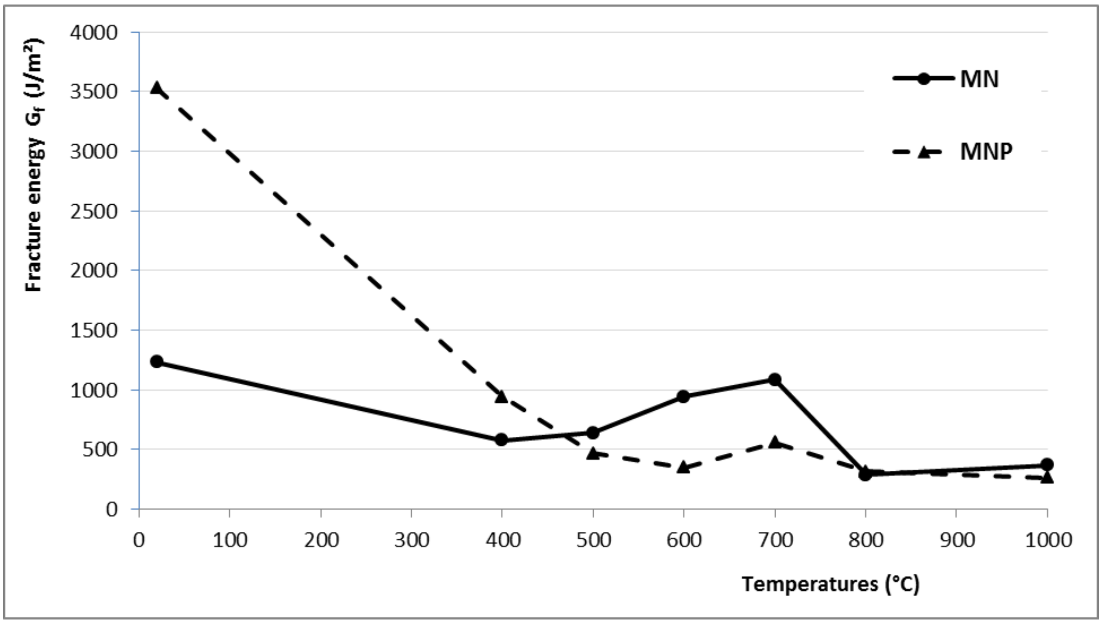

Figure 5: Evolution of the fracture energy with respect to the exposure temperature.

Table 5: Evolution of the fracture energy G_f (J/m²) with respect to the exposure temperature.

Mortar	T°C	20°C	400°C	500°C
MN		1234	577	639
MNP		3531	943	468

3.5. Stress intensity factor

The stress intensity factor K_I characterizes the resistance of material to the propagation of the crack and to the damage [16-18]. This parameter can be deducted from the calculation of the fracture energy G_f and of the Young modulus E. It is defined by the following relation:

$$K_I = \left(G_f . E\right)^{0.5} \quad \text{(eq. 1)}$$

This parameter takes into account the degradation of the cement matrix; rather quantifiable by the young modulus and the fibre degradation (modification of the characteristics of fibres, loss of cohesion), rather quantifiable by the fracture energy. This is thus a representative parameter of the overall damage of the fibrous material.

The evolutions of the stress intensity factor of the mortars with respect to the exposure temperature are illustrated in figure 6 and table 6.

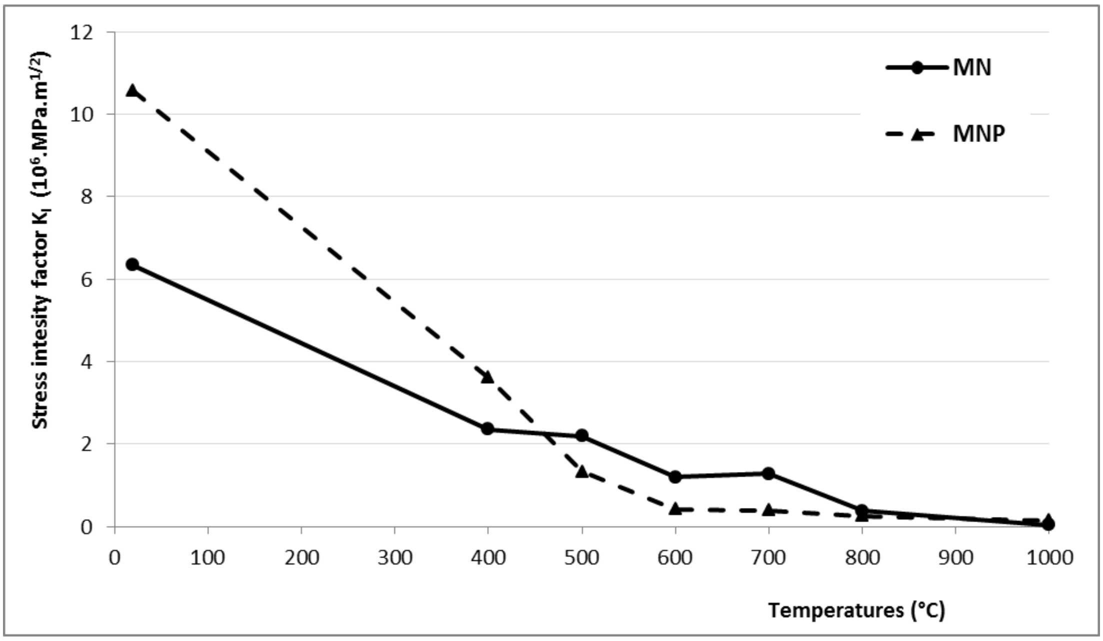

Figure 6: Evolution of the stress intensity factor K_I with respect to the exposure temperature.

Table 6: Evolution of the intensity factor K_I (10^6 MPa.m^{½}) with respect to the exposure temperature.

Mortar T°C	20°C	400°C	500°C
MN	6,3	2,4	2,2
MNP	10,6	3,6	1,3

According to the test results (figure 5 and figure 6), we notice that the fracture energy and the stress intensity factor have similar behaviour when exposed to equivalent temperatures.

The stress intensity factor for the fibre mortar K_I has a great value at 20°C and 400°C. Beyond this limit, we observe a very pronounced decreasing of the stress intensity factor. This decrease is mainly due to the fact that the polypropylene fibres have certainly totally melted and calcined. The fibres that stop crack propagation are no longer present.

At the high temperatures, two types of damage appear: (1) the physicochemical modifications and (2) cracking of the cementing matrix [11, 19, 20]. Results from a previous study showed that the polypropylene fibres had more effect on the reduction of cracking than on the reduction of the physicochemical modifications [21]. From 170°C, the polypropylene fibres melt and create a connected porosity [22]. This porosity allows evacuating vapour over-pressures and thus reducing cracking [23]. This weaker cracking explains the best results in term of resistance, ductility and fracture energy or stress intensity factor.

Moreover, when the temperature of the furnace is 400°C, the temperature inside the specimen is lower and can be not sufficient to destroy all fibres. The propagation of heat is slowed down in the dehydrated cementing matrix [11-17]. The fibres disappear gradually from the periphery of the sample towards the centre: the kinetics of propagation of heat is slowed down by the more or less insulating dehydrated cementing matrix [8]. Fibres remain in the heart of the sample and contribute to the ductility of material. Beyond 500°C, the fibres completely disappeared to create an additional porosity [22-26]. This porosity leads thus to a lower energy than that of the not fibred samples. This process has been observed by optical microscopy (figure 7). Small slice extracted from different depth of a sample exhibits completely calcined polypropylene fibres in the first millimetres. Deeper slice contains yet partially melted fibre.

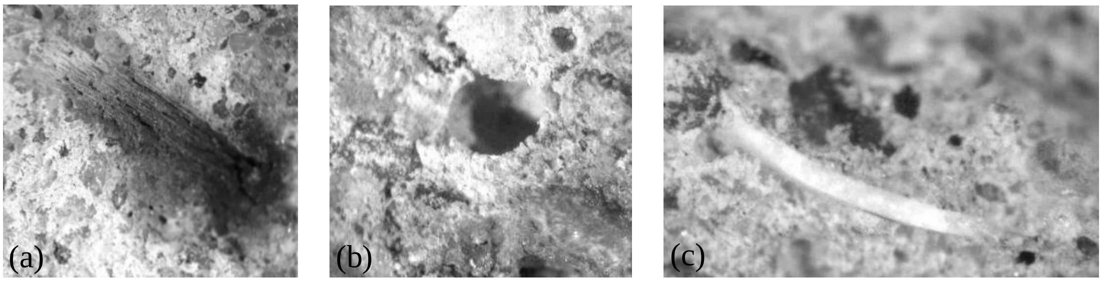

Figure 7 : Optical microscopy observations. (a) Calcined fibre. (b) Melted Fibre. (c) Partially melted fibre.

4. FLAME TEST

4.1. Exposure to fire

The second heat treatment consists of placing plates of dimensions 16x16x4 cm^3 made of unreinforced mortar and polypropylene fibre reinforced mortar in a flame test apparatus (figure 8a). Five thermocouples were inserted in the plate (figure 8b) at different depth and two other thermocouples were positioned in contact with the internal face (hot face) and external face (cold face) (figure 8c). The temperature of the exposed face (dimensions 16x16 cm^2) is forced to 1000°C and was maintained for one hour. Figure 9 compares the rate of temperature between the experimental curve and the ISO 834 standard fire. The experimental rate of temperature is similar to that of ISO 834 up to 1000°C. This rate leads to a strong temperature gradient in the sample. The sample dimensions are assumed to be enough to observe spalling.

The heat flux is assumed to be unidirectional. The flame position allows setting in a precise manner the temperature of the surface.

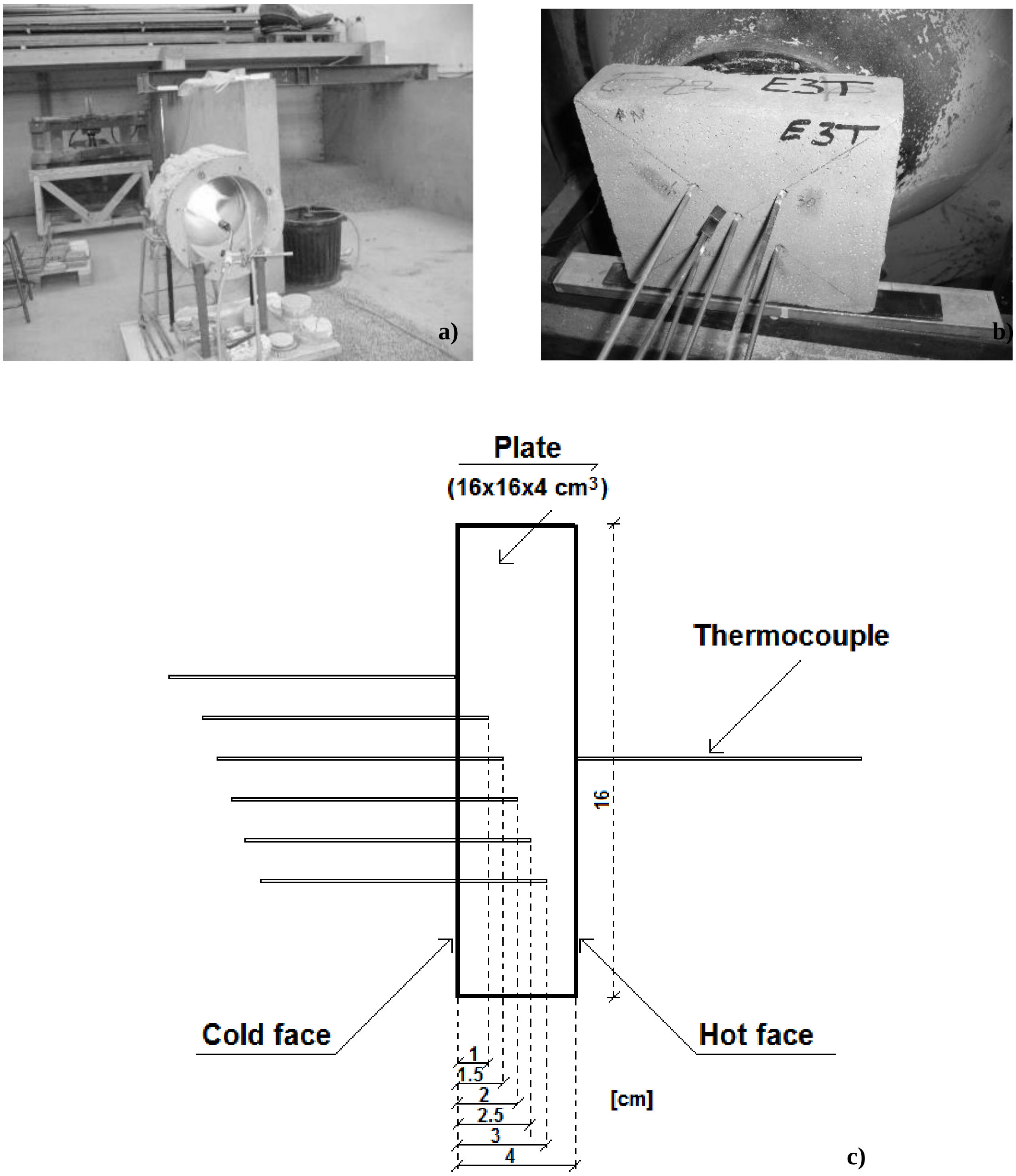

Figure 8: a) mounting flame test, b) drilled external face,

c) thermocouples position.

Two series of test were performed:

- First series (equipped with 7 thermocouples (type K)): the evolution of the temperature of this series is obtained by placing thermocouples (drilled after casting) at different depths of the sample (external face – 1 cm – 1.5 cm – 2 cm – 2.5 cm – 3 cm, and the internal side) as illustrated in figure 8c.
- Second series (equipped with 2 thermocouples): thermocouples were positioned in contact with the external (cold face) side and at the internal (hot face) side. It has to be noted that this thermocouple measures radiation and convection from the flame, rather than surface temperature at the exposed face. However it was very difficult to achieve the measuring of the surface real temperature.

At the end of the test, cooling was performed naturally at room temperature. Punching shear tests were, then carried out for a comparison.

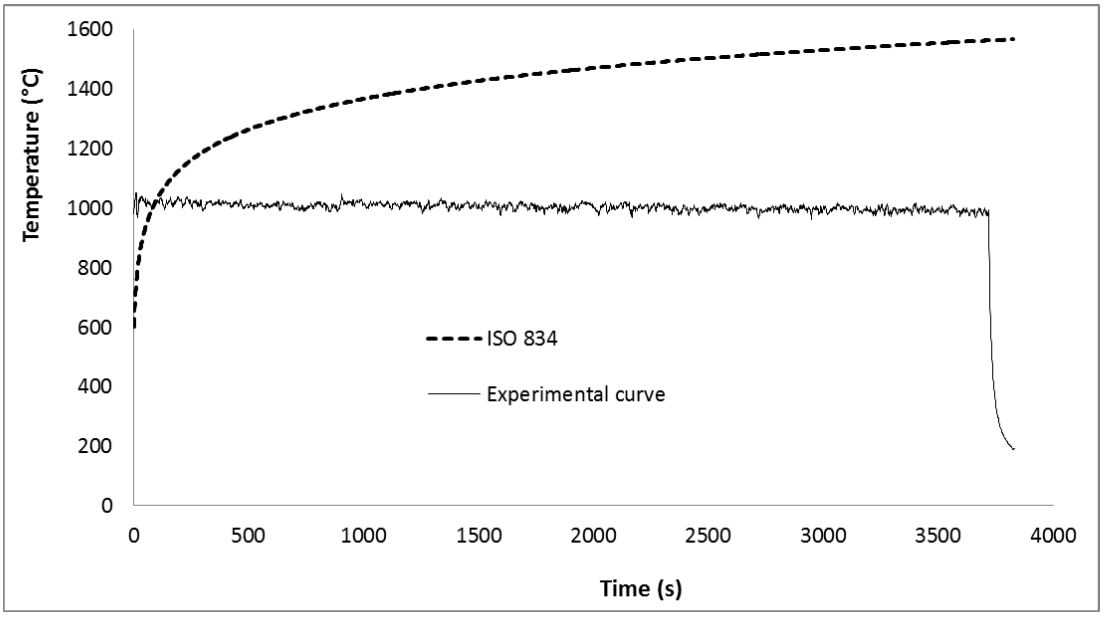

Figure 9: Comparison between ISO 834 fire and the experimental curve.

4.2. Heat transfer

During these tests, and after 5 minutes of treatment, we observed, drops of water and water vapour escaping from the drilling of thermocouples of the unexposed surface of the test sample for the 2 types of mortars. Nine minutes after treatment, we observed the apparition of a fist crack in the standard mortar. This crack has developed from lateral side to the centre. However, this phenomenon did not appear for fibre reinforced mortar.

Figure 10 shows the evolution of the temperature of both mortars with respect of time and depth. The temperature evolution consists of three stages: a rapid increase of the temperature until 100°C, an isothermal stage around 100°C and an increase of the temperature. The isothermal stage around 100°C corresponds to the evaporation of free water at different depths. Mindeguia et al., [8] observed this plateau at 100°C for low compactness concrete.

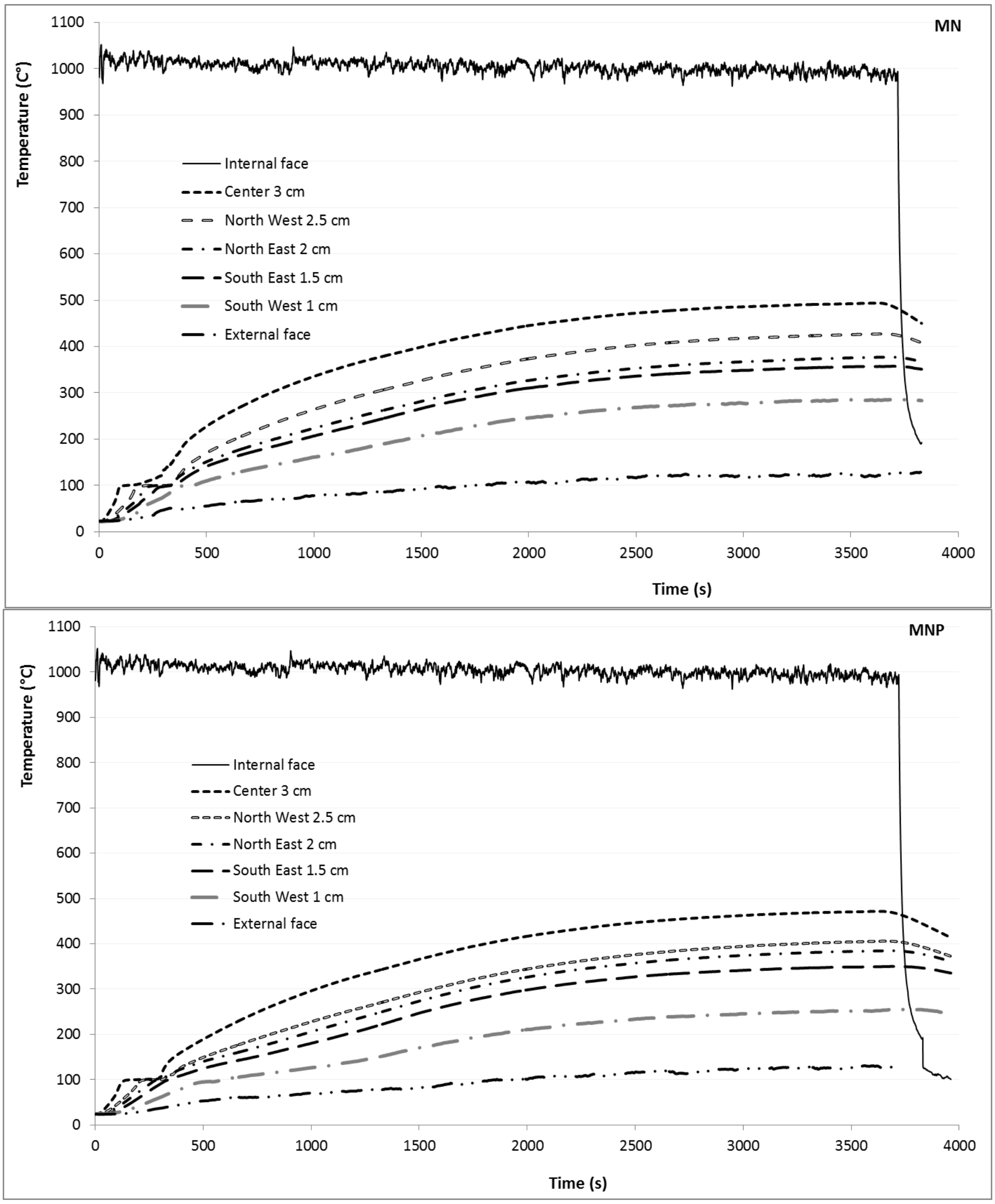

Figure 10: Evolution of the temperature at different depths of the non-fibre mortar and fibre mortar.

It is this possible to quantity the heat propagation in the two mortars using the temperature measured by thermocouples. To check the effect of drilling on this transfer, plates were tested without drillings (without thermocouple), and only hot face temperature and cold side temperature were measured. It was seen that the temperature at the external face is similar for plates with and without drilling. Temperature gradients in plates made of standard mortar and fibre reinforced mortar are shown in figure 11. The presence of polypropylene fibres does not lead to significant changes in the phenomenon of heat propagation. The temperature at 3 cm depth (i.e at 1 cm of the hot face) does not exceed 500°C. In the outer face (i.e. at 4 cm from the hot face), the temperature reaches approximately 140°C after one hour of exposure.

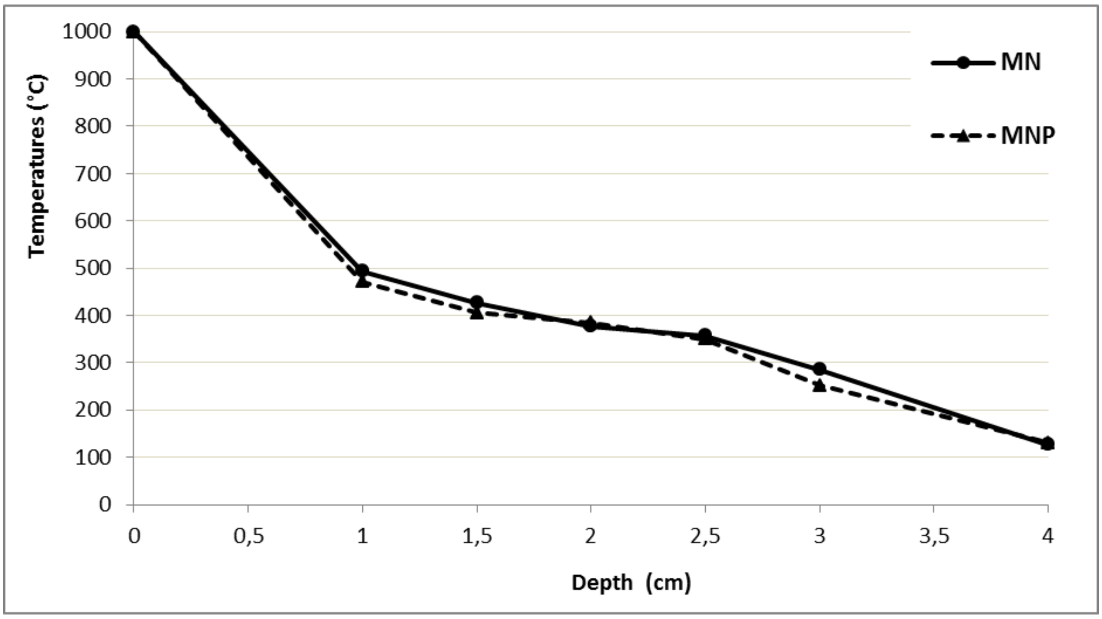

Figure 11: Thermal gradient within test specimens after one hour of thermal exposure during flame tests.

4.3. Mass loss after tests

The mass loss at the end of the test is almost identical for the two mortars. The mass loss of the standard mortar (MN) and fibre mortar (MNP) is 6.4% and 6.5% respectively. We can say that the fibres embedded in the mortar have virtually no influence on the evaporation of water from mortar and hydroxides OH after this heating. Similar observations were reported by [27].

4.4. Residual strength

Subsequently, to enable a comparison between the residual mechanical strength of samples a punching shear strength [28] test was performed on non-drilled samples as presented in figure 12. Results are reported on table 7. Each value is the mean between ten samples; the difference between these ten values is maximum 3%. Before flame exposure, punching shear strengths are quite similar for the two mortars. After flame exposure, all mortars show a loss of punching shear strength. Fibre mortars have a lower residual strength compared to those without fibres: strength reduction is 64.5% for mortar without fibre and 73.7% for mortar with polypropylene fibres. A temperature of 1000°C at the hot face for 1 hour conducts to temperature greater than 170°C (polypropylene melting) up to about 1 cm from the cold face: it can be considered that all fibres were completely melted up to about 1 cm from the cold face. The induced porosity due to the degradation of the fibres decreases the strength. However, after heating, a part of polypropylene fibres is still present in the outer face side. The cold face temperature is only 140°C after one hour, while the melting point is given at 170°C. Thus, the strength loss is limited. These results are consistent with the results obtained in a preliminary study [29].

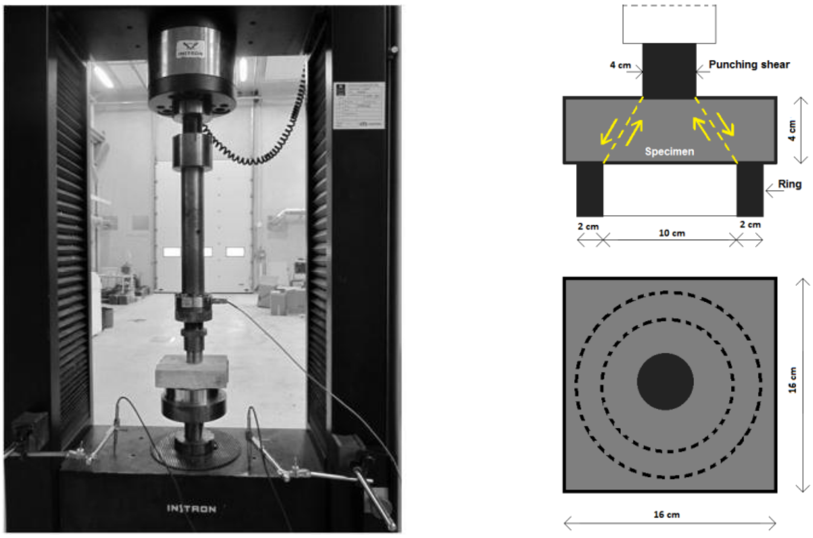

Figure 12: Test bed to punching shear.

Table 7: Residual punching shear effort of the plates after testing at flame.

	Non-heated	Heated
Mortars	F_{max} (kN)	F_{max} (kN)
Non-fibre	20.3	7.2
Fibre	20.9	5.5

4.5. Spalling during heating

Induced porosity due to melting of polypropylene fibres is considered to facilitate the transfer of steam and avoid spalling [23, 30, 31]. It is reasonable to consider that concrete incorporating polypropylene fibre can provide a benefit to concrete so as to prevent it from explosive spalling, due to the fact that it is melted under temperature around 170°C and hence accumulated moisture pressure in concrete can escape through inter-connected pores to outside of concrete. Samples from mortars with and without fibre at a water to cement ratio equal to 0.5 did not spall. However, other tests with polypropylene fibre reinforced mortars with the same fibre volume ratio but a water/cement ratio of 0.4 spalled during testing (figure 13). Similar observations were conducted in studies on concrete with low water/cement ratio (concrete with 0.26 water/cement ratio and 1 kg/m^3 of polypropylene fibres spalled, but concrete with 0.26 water/cement ratio and 0.6 kg/m^3 of polypropylene fibres and 40 kg/m^3 of steel fibres did not spall [32]) or on lightweight concrete (concrete with 0.33 ratio spalled, and concrete with 0.42 ratio did not spall [5]).

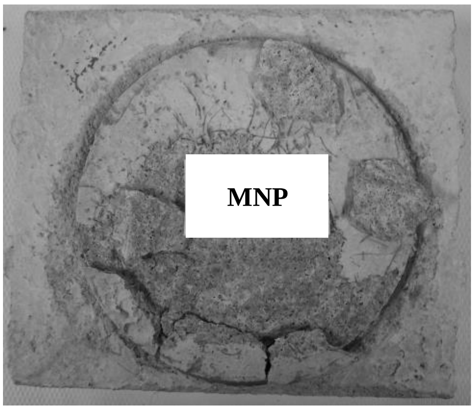

Figure 13: Example of spalling of sample made with 0.58% polypropylene fibre and w/c=0.4.

7. CONCLUSION

This study highlights the contribution of polypropylene fibres in cement based building materials exposed to an increasing temperature or exposed to flame. We have studied the mechanical behaviour of standard mortars and fibre reinforced mortars heat-treated at 400°C, 500°C, 600°C, 700°C, 800°C and 1000°C. Two types of treatment have been made: a heating furnace (low rate) and an extreme heated test with flame (high rate).

At room temperature (before heating), the post peak stress clearly highlights the role of the fibres: the stress transfer between the faces of the cracks by polypropylene fibres is important and gives samples ductility.

After heating, below 400°C, the fibres have an uncracking effect by allowing the dissipation of fluid over pressure in the matrix. This phenomenon disappears at a temperature over 500°C. The fibre samples have greater young modulus compared to that of the non-fibred ones with an increasing gap until a temperature of 400°C and decreases beyond this value. At 500°C, they are identical. After 500°C, the young modulus becomes almost zero. The fracture energy at 20°C is 3 times greater for the fibred samples compared to the non-fibred ones. This ratio drops to 1.5 at 400°C. Fibres effects are negative beyond the temperature of 500°C.

It appears, from the flame test that the fibre mortar and non-fibre mortar have the same thermal behaviour. After one hour, the unexposed side is about 140°C.

For the residual punching strength; the results show that polypropylene fibres are not so efficient: the polypropylene fibres limit the cracking during heating but do not increase the punching strength.

By melting at 200°C the polypropylene fibres are considered to create a porosity which allows a limitation of the pressure due to the evaporation of water treatment and thus a limitation of cracking. The spalling phenomenon was not observed for all mortars having a water/cement ratio of 0.5. However, spalling was observed for mortars with water/cement ratio of 0.4.

For design of concrete structures, it has to be noted that the temperature remains below 500°C after two centimetres inside the concrete (i.e. after the cover over reinforcing steel). Up to 500°C, polypropylene reinforced mortar gives a pseudo-ductile behaviour with a better strength, a better Young modulus, a better fracture energy than mortar without fibre. Thus, the safety of concrete structures submitted to fire is increased. After fire, the rehabilitation of concrete cover will be limited and associated cost decreased.

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